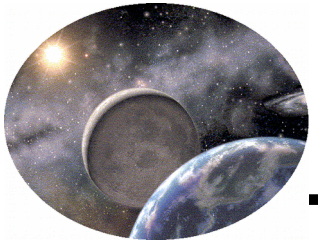


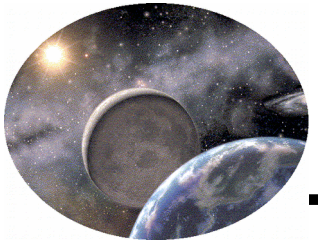
BOEING

Building Star Catalogs for Spacecraft Applications

Leonard J. Berg

December 5, 2000

Washington, D.C.

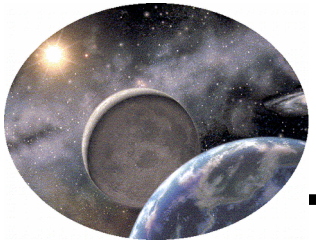


Agenda

Building Star Catalogs for Spacecraft Applications

BOEING

- **Background**
- **Introduction**
- **Requirements**
- **Input Databases**
- **Generation Process**
- **Commentary**

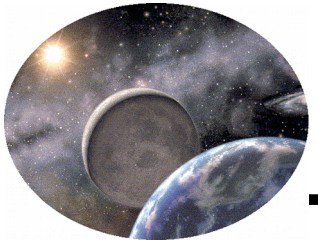


Background

Building Star Catalogs for Spacecraft Applications

BOEING

- **Personal History**
  - Assignment to build master star catalog in 1994
    - *Position and proper motion reference for FK4-FK5 upgrade*
  - Obtained list of USNO-recommended catalogs
    - *FK5 (including extension), IRS, ACRS (Parts 1 & 2), CPIRSS*
  - Attempted to find matches for stars in existing user catalogs
    - *Dozens of user stars missing (brighter than magnitude 6)*
    - *Added comprehensive catalog database (some still missing)*
    - *Filled in with SAO catalog (earlier source reference)*
  - Reservations about completed catalog
    - *Proper motion accuracy*
    - *Significant star intensity discrepancies (between sources)*
    - *Visual positions for IR stars*
    - *Merge process suspect when near neighbors exist*
    - *Nagging feeling that some stars still missing*

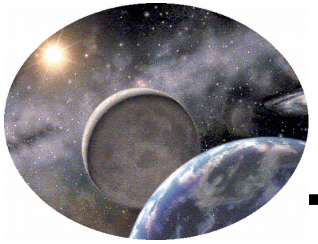


Introduction

Building Star Catalogs for Spacecraft Applications

- **Space vehicles need star catalogs to ...**
  - Design onboard attitude determination software
  - Simulate on-orbit performance (will design work?)
  - Initialize attitude reference (where am I?)
  - Maintain accurate onboard attitude reference
  - Calibrate sensors (biases, alignments, scale factors, etc.)

  Note: Accuracy critical for precision systems
- **Catalog effectiveness dependent on available resources**
  - Hundreds of star catalogs exist
  - Each catalog intended to serve specific objectives
  - All catalogs are missing critical information
  - Not always obvious which combination of catalogs to use
  - Difficult to identify inaccuracies, errors, and missing data
- **Build process is simple ... *in principle***
  - Select appropriate input databases
  - Filter catalogs based on requirements
  - Validate results



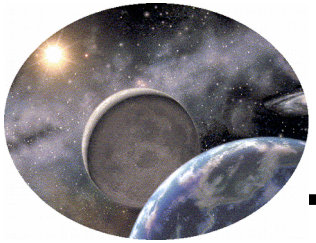
Requirements

Building Star Catalogs for Spacecraft Applications

- **Reference Catalog Requirements**
  - Include ALL ...
    - *Observable stars (e.g. $V_{SENSOR} \leq 6.0$)*
    - *Potentially interfering near neighbors (e.g. $V_{SENSOR} \leq 11.0$)*

    Note: Actual threshold dependent on sensor selected
  - Astrometry must support error budget
    - *Position and proper motion for all input catalog stars*
    - *Parallax for all observable stars*
  - Must enable conversion to sensor magnitude
    - *Spectral class plus magnitude or 2-color photometry*
    - *Consistent luminosity scale for all input catalog stars*
    - *Variability data required to support exclusion algorithms*
  - Define unique characteristics
    - *Draw attention to potential problem stars*
  - Reference frame must be consistent with program geodesy
    - *International Celestial Reference Frame*

    Note: Assumes compliance with ITRS and IERS Conventions



Input Databases (1 of 3)

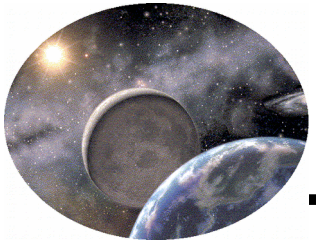
- **Hipparcos Star Catalog**

Reference system	*ICRS J2000.0*
Number of entries	*118,218 stars*
Completeness	*V = 7.3 mag*
Limiting magnitude	*V ~ 12.4 mag*
Position accuracy	*0.77/0.64 mas*
Parallax accuracy	*0.97 mas*
Proper motion accuracy	*0.88/0.74 mas/yr*
Photometric precision	*0.0015 mag*
Variable stars	*11597 (8237 new)*
Double/multiple stars	*23882*

Conclusions

- *Excellent resource for 53k brightest stars (V = 7.3)*
- *Probably includes all useful onboard catalog stars*
- *Provides H_P, B_T and V_T magnitudes*
- *65k additional stars selected based on astrophysical or astronomical interest*
- *Larger catalog required for near neighbor analysis*

Launched in 1989 by the European Space Agency (ESA), the Hipparcos satellite was designed to spin slowly, completing a full revolution once every 2 hours. By slowly changing the orientation of the rotation axis, the telescope was able to scan the entire celestial sphere several times during its mission. 'Hipparcos' is an acronym for HIgh Precision PARallax COllecting Satellite and is a play on Hipparchus – a Greek astronomer who lived from 190 to 120 BC.



Input Databases (2 of 3)

Building Star Catalogs for Spacecraft Applications

BOEING

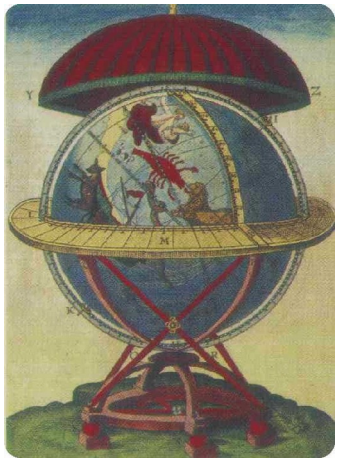
- **Tycho-2**

Reference system	*ICRS J2000.0*
Number of entries	*2,539,913 stars*
90% complete	*V ~ 11.5 mag*
99% complete	*V ~ 11.0 mag*
Position accuracy	*7 mas (V_T < 9)*
Proper motion accuracy	*2.5 mas/yr (all stars)*
Photometric precision	*0.013 mag (V_T < 9)*

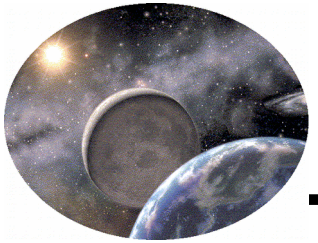
Conclusions

- *Excellent catalog for near neighbor analysis*
- *Proper motions derived from 144 catalogs*
  - *Not available for ~4% (mostly faint end)*
  - *Positions are not J2000.0 in these cases*
- *Provides B_T and/or V_T magnitudes (usually both)*
- *Missing some Hipparcos and Tycho-1 stars*
  - *Instrument saturation at V_T ~ 1.9*
  - *Some Tycho-1 stars excluded for various reasons*

GLOBUS MAGNUS

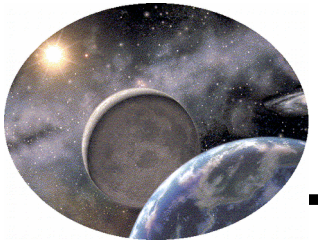


Tycho Brahe had this 5' diameter wooden globe built in 1570 when he was an astronomer for the mayor of Augsburg, Denmark. After 25 years, it included accurate positions for 1000 fixed stars. It went with Brahe to Bohemia, was brought back to Copenhagen as war booty in 1632, and was destroyed by fire in 1728.



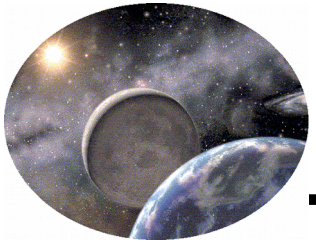
Input Databases (3 of 3)

- **Other Supporting Catalogs**
  - Tycho-1 Catalog
    - *Original 1,058,332 stars processed from Tycho data*
    - *Includes some poor quality objects not listed in Tycho-2*
  - Hubble Space Telescope Guide Star Catalog
    - *Almost 19 million objects (15 million classified as stars)*
    - *Merged with Tycho-1/Hipparcos data*
    - *No proper motion data*
  - Precision Measuring Machine Catalogs (USNO-A2.0)
    - *526,230,881 stars from three photographic sky surveys*
    - *Only includes stars observed through both B and V filters*
    - *No proper motion data, poor photometry*
    - *USNO-SA2.0 is a subset selected to give uniform distribution*
  - General Catalog of Variable Stars (GCVS)
    - *Contains data for 35,148 variable objects*
    - *New data added frequently*
  - Washington Double Star (WDS) Catalog



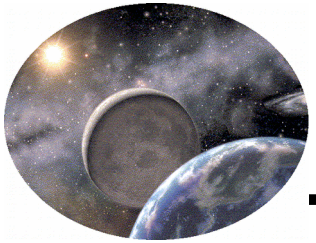
Generation Process (1 of 2)

- **Create All-Sky Catalog**
  - Merge Hipparcos and Tycho-2 catalogs
    - *Eliminate duplicates*
    - *Keep data from most accurate source*
- **Convert Magnitudes to In-Band Values**
  - Transform to V_{SENSOR} in merged catalog
    - *Based on H_P, B_T, V_T, and spectral class from Hipparcos/Tycho*
    - *Validate conversion subroutines using star tracker vendor data*
    - *Apply variability and potential errors to compute min/max*
- **Filter Catalog Based on Star Observability**
  - Exclude stars the sensor may not see or accurately resolve
    - *Include worst-case variability in analysis*
    - *Keep a log of marginal stars*
    - *Thresholds are sensor dependent*



Generation Process (2 of 2)

- **Exclude Stars with Optically Near Neighbors**
  - Find stars with neighbors close and bright enough to shift position
    - *Analysis must cover potential mission duration*
    - *Use all-sky catalog created earlier for comparison*
    - *Also refer to Washington Double Star Catalog*
    - *Keep a log of excluded stars*
    - *Exclusion criteria sensor dependent*
- **Review Results**
  - Analyze catalog for acceptable coverage across the celestial sphere
    - *Review marginal stars in regions of concern*
    - *Weigh benefits/risks of using each star*
    - *Determine whether and how to plug holes*
  - Perform additional catalog verification using independent resources
    - *Look for and resolve issues with problem stars*
- **True-of-Date Conversion Options**
  - Precession, nutation, proper motion, and parallax compensation
    - *Ground maintenance with periodic updates OR*
    - *Onboard processing*

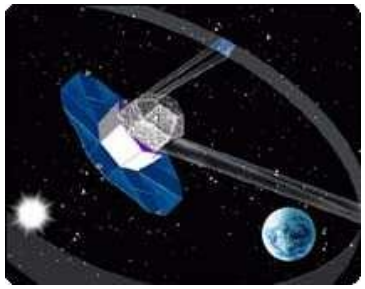


Commentary (1 of 2)

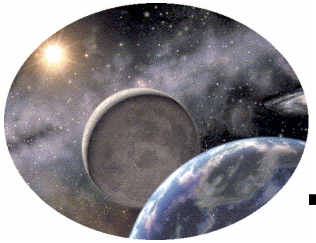
Building Star Catalogs for Spacecraft Applications

- **Scientific Community Focus**
  - Exploring depths
    - *More exciting than surveying breadth*
    - *Spacecraft applications not first priority*
  - NASA science themes
    - *Astronomical search for origins*
    - *Structure and evolution of the universe*
    - *Sun-Earth connection*
  - FAME science objectives
    - *Calibrate luminosity for galactic distance*
    - *Enable diverse studies of stellar evolution*
    - *Determine the ages of globular clusters*
    - *Discover prevalence of large planets*
    - *Research stars in star-forming regions*
    - *Assess dark matter in the galactic*

FAME



Scheduled for launch in 2004 as one of NASA's Office of Space Science MIDEX programs, the Full-sky Astrometric Mapping Explorer (FAME) will address several key questions related to each of NASA's science themes while accurately measuring the positions, proper motions, parallaxes, and photometry of 40 million stars. This represents nearly all stars brighter than 15th visual magnitude during a baseline mission



Commentary (2 of 2)

Building Star Catalogs for Spacecraft Applications

- **Spacecraft Applications Community Wish List**
  - Catalog that includes ALL observable and potentially impacting stars

Completeness	*7.0*	*12.0*	*mag*
Position accuracy	*1.0*	*10.0*	*mas*
Proper motion accuracy	*0.1*	*1.0*	*mas/yr*
Parallax accuracy	*1.0*	*10.0*	*mas*
Photometric precision[1]	*0.002*	*0.02*	*mag*

[1] Required in at least 2 bands (B and V)

  - Uniform criteria and photometry for double/variable star data
  - Visual and infrared position discrepancies identified
- **Conclusion**
  - Bright future
    - *Opportunity to support improved spacecraft application catalogs*